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Miriam: Welcome back to Great Mysteries of Physics from The Conversation. I'm Miriam Frankel and I'm your host for the series.

In this series, we've explored five different but equally great enigmas of physics, but why is physics so full of mysteries? Is it an indication that it is in fact broken? That's what we'll discuss this time.

Our two best theories of nature are quantum mechanics and general relativity describing the smallest and biggest scales of the universe respectively. Each is tremendously successful and each has been tested experimentally over and over. The trouble is however that they clash. Quantum mechanics is riddled with randomness, entanglement and fundamental uncertainty that we don't see in general relativity. And while time in quantum mechanics is absolute, it is relative in general relativity. So physicists have long been trying to come up with frameworks for unifying the two into a theory of everything. Popular approaches include string theory or loop quantum gravity, but these theories apply on scales that are difficult to test experimentally, requiring much more energy than we can currently produce in the lab. That said, physicists have managed to unite quantum theory with Einstein's other big theory, that of special relativity. Together, they form something called quantum field theory, which is the basis of the standard model of particle physics, which is our best theory to describe the most basic building blocks of the universe.

And while the standard model seems to be able to describe a lot of the experimental results that we can actually produce, there are some gaps. And particle accelerators have failed to discover the very particles that would close those gaps. At the same time recent results from particle physics experiments hint that there may be forces and particles still to be discovered, potentially even mandating new physics.

So what's going on? Will physicists ever develop a theory of everything? What would happen if they didn't? And if they did, could we ever test it?

Vlatko Vedral is a Professor of Physics at the University of Oxford in the UK. He says that trouble with uniting quantum mechanics and general relativity is partly down to the different mathematics they use.

Vlatko Vedral: I think even at a simpler level, possibly before we even start discussing things like physical notions of space and time, you could actually argue that the two theories are based on different kinds of mathematics, interestingly enough. So just if you look at it not as a physicist necessarily, as a mathematician, you would say that general relativity is all about geometry. It's how space is curved and how spacetime ultimately, this unified entity that contains three dimensions of space and one dimension of time, is itself also curved. And in fact, gravity is just a manifestation of this curvature of spacetime, all about geometry. Whereas quantum physics is actually all about algebra. It's what we call linear algebra. So there are even two different branches of mathematics, which is interesting. Even at that level the question is how do we put this together now?

Miriam: Yeah .Yeah. I think that is why I always preferred quantum mechanics, because I like algebra. Yes. And I do not like geometry.

Vlatko Vedral: Yeah. And by the way, it may explain why people like Roger Penrose, who is extremely intuitive in terms of geometry, he's all about visual things, why actually he tends to prefer a general relativity and he thinks quantum mechanics will collapse ultimately.

Miriam: Interesting how it can come down to those kinds of preferences that we intuitively feel closer to one of the two theories. That's a really interesting point. What about you?

Vlatko Vedral: I am probably among people who weirdly enough, uh, may not think that there is a problem, at least in the foreseeable future.

Miriam: But you're saying you don't think there is a problem, but if there was a problem, what's your hunch? Which one do you think is more likely to have to be modified?

Vlatko Vedral: My intuition would be both, and it's simply based on a historical observation. I don't think I can base it directly on general relativity or quantum mechanics, but if you looked at how theories in the past were modified, even when we had a tiny discrepancy in our theories, even when something small could not be explained, then what it usually required is a radical modification. And this, we see both with relativity and quantum mechanics. They're not just small departures. So we had to change classical physics in two very different ways to arrive at relativity and quantum mechanics. And my feeling now is that the next revolution, if there is such a thing, I, I hope that there is such a thing. I'm almost betting on that. Um, uh, that revolution will somehow unify both into a completely different theory. And then you will take a special limit and derive general relativity in that limit. You will take another limit and derive quantum mechanics, but when you put them together, they will lead to some new entities. And then we will end up discussing the philosophical meaning of these new structures and what is the nature of reality. And all of these questions would happen in the new theory.

Miriam: So Vlatko isn't necessarily expecting physics to persevere with just small tweaks to our best theories. Just as general relativity and quantum mechanics in different ways ended the common sense physics before them, a new theory of everything may be a radical departure from the physics we have today. But before we get to that, let's just consider the standard model of particle physics.

Vlatko Vedral: The standard model, I think most people would agree, is very heuristic in many ways. So it's the best description we have that unifies, certainly special relativity, at least with quantum mechanics. What, what we call quantum field theory.

Miriam: But it's not a theory like quantum mechanics, original relativity.

Vlatko Vedral: You're right. Not really it is, um, it's a model or how would you, it's a model that contains probably far too many fundamental constants that already shows you that somehow we don't really understand it very well because it really should boil down to possibly, you know, Newton's gravitational constant, uh, speed of light, Planck's constant as we understand nature at present. But going beyond it, it seems unnecessary somehow, which usually signals that it's not the most compressed theory that we could come up with. There must be something going beyond this.

Miriam: Fundamental constants are quantities that we have to measure from an electron's charge to the mass of a quark. There's simply no theory explaining what values they should have. So ideally we need a deeper theory of everything to tell us that.

Vlatko Vedral: That's it. So it says that we have these fundamental particles which constitute matter, and then we have particles which constitute what we would call forces. They're exchanged between these material elements, quarks and electrons. So we exchange photons, for instance, which are the particles of light, and that's the electromagnetic force, or you exchange gluons, for instance, which would glue, as the name suggests,they would glue quas together into proteins and neutrons and then glue these together into atomic nuclei. So there are these handful of fundamental particles and the standard model contains them, but the interactions between them and their various properties, like I said, are not really explained. They're taken as given, as constants if you like, but they look remarkably arbitrary. If you think about it, it almost begs a question to go beyond it and to understand them, why they are the way they are.

Miriam: General relativity sits outside the standard model of particle physics with quantum field theory, failing to describe the force of gravity.

Here's Chanda Prescod-Weinstein an Assistant Professor in Physics and Astronomy and Core Faculty in Women's and Gender Studies at the University of New Hampshire. She's also author of 'The Disordered Cosmos, A Journey into Dark Matter, Spacetime and Dreams Deferred'.

Chanda Prescod-Weinstein: It doesn't come in at all. In fact, the astute science reading General Public has probably heard many times over the last decade, particularly since we observed the Higgs at the Large Hadron Collider, that the standard model is finished, it's complete. I could point to a couple of places where that's just like patently, not true. Like what I think is turning out to be extraordinarily bad PR. I understand why people use that line, but it's backfiring a lot and it's not true. But one of the things that it's missing is that it explains three of the known forces, but not the fourth one, which is gravity.

Miriam: So the three ones being electromagnetism and, uh, the two nuclear forces?

Chanda Prescod-Weinstein: The weak nuclear force and the strong nuclear force.

Miriam: Yeah. Okay. So we have four known forces. So the standard model and quantum mechanics explain and work with three of them, and then gravity in the fourth, general relativity and gravity.

Chanda Prescod-Weinstein: I find all of these nomenclature questions about, do we call it gravity? Do we call it relativity to be really interesting? But there are a lot of ways in which gravity is just really weird. And one thing that distinguishes it as a mathematical picture and even as a physical picture, is that general relativity is geometric by nature, right? So the way that people have maybe heard references to this is through. The idea that spacetime is curved or that spacetime can curve and that really one of the lessons of Einstein's general relativity is that when there's a massive object in spacetime, it causes the spacetime to curve and the curvature of that spacetime tells the object how to move, which I'm very badly paraphrasing, I think John Wheeler. But there's a dynamical relationship there where they are creating movement in each other and it's a kind of dance, a partnership between spacetime and massive objects. The standard model is not geometric in that way. And so again, really I think the thing that fascinates me about these questions is how do you bring those two into conversation with each other when they're really living in different mathematical worlds?

Miriam: So given that gravity is the odd one out, does that mean it is perhaps not a fundamental force unlike the other three? Or are quantum field theory and the standard model simply wrong? While the standard model has been enormously successful at explaining experimental results, it does contain a few gaps. And to bridge those, an extension called supersymmetry, suggesting that particles are connected through a deep relationship has been suggested. According to supersymmetry, each particle has a super partner with the same mass. But opposite spin, for example, the electron would have a super partner called the selectron. Interestingly, supers symmetry is also an important feature of string theory, but so far, particle accelerators such as the Large Hadron Collider at CERN in Switzerland have not found any such partners. Despite being explicitly designed to do so, threatening both the idea of supersymmetry and string theory.

Chanda Prescod-Weinstein: I do think that we have to redevelop an appreciation for incremental learning and an appreciation, and this was actually something that I picked up from a conversation with, um, a particle experimentalist at University of Texas, Peter Onyisi. That not finding something is science. That's a piece of information. We now know that the particle does not have the particular properties we were looking for. That's information. So then what we got out of the LHC was the Higgs and the Higgs Boson was a huge accomplishment, and that was really kind of like the cherry on the top in terms of the basic pieces of the standard model that we were looking for. But no supersymmetry observations emerged from any of the experiments that happened afterwards. So there are some people in the community who have used this fact to argue that supersymmetry as a theory is dead. It's a hypothetical.

Miriam: And thereby also string theory?

Chanda Prescod-Weinstein: Yeah, it's possible. There's a string theory out there that doesn't require supers symmetry, but not that I know of. So I think that that would really be kind of the nail in the coffin for string theory. I am actually not in the community of people who think that Susy, as people sometimes call super symmetry, is dead and shouldn't be studied anymore. There's no cosmic rule saying that the energy scale of supersymmetry would be at the energy scale that the LHC was built for. So there is one model of supersymmetry, which was the simplest and lowest energy one that's basically been ruled out.

Miriam: Okay. But there are other models with different energy that just we haven't been able to probe.

Chanda Prescod-Weinstein: Yes. And I am a firm believer in pursuing what's possible, until we know for sure that it's not possible.

Miriam: Even though the LHC hasn't found any super partners yet, it has come across a strange anomaly lately. In fact, both the LHC and the Muon g-2 experiment at Fermilab in the US. Have discovered hints of new and surprising physics. Detailed studies from the LHCb experiment found that a particle known as a beauty quirk, so quarks are particles which make up nutrients and protons in the atomic nucleus decay into an electron much more often than it decays into an electron's heavier cousin called a muon. And according to the standard model, that shouldn't happen, hinting that new particles or even forces of nature may be influencing this process. The uncertainty of this result is over three sigma, meaning that there's a one in a thousand chance that the result is a random fluke. And conventionally particle physicists call anything over three sigma evidence while five sigma would be needed for a confirmed discovery. And that's a one in a million chance that the findings are just random. The Muon g-2 experiment meanwhile, has recently investigated how moans wobble when magnetic fields interact with their spin.

It found a small but significant deviation from some theoretical predictions, again, suggesting that unknown forces or particles may be at work. And the chances of this discrepancy being a fluke is about one in 40,000, so also below the threshold of what can be considered a discovery. Fermilab has also made a surprising measurement of the mass of a particle called the W boson, and that suggests that the particle is significantly heavier than theory predicts, and this result is in fact impressive deviating by an amount that would not happen by chance in more than a million, million experiments. However, a reanalysis of old data from the Large Hadron Collider's ATLAS experiment just recently contradicted this by indicating the particle's mass is in line with the standard model. So at the moment we simply don’t know and the debate is likely to go on.

The findings could be explained by an alternative theory to supersymmetry, suggesting there's a fifth force of nature. And that would mean that the Higgs particle may not be a fundamental particle, but instead made up of other fundamental particles bound together by this unknown force. But how seriously should we take this? Is it actually evidence?

Vlatko Vedral: Oh, I think that would be amazing. Again, it would challenge these things that now existed for well over half a century, that there are four fundamental forces. Like I said, we are still uncertain about gravity. Uh, there are various views, but I think coming up with another force would definitely radically change this. It would make matters more complicated. I haven't taken this as seriously myself, simply because I think already this question of gravity is very big, and I think with gravity, we literally have no experiments telling us either way. And it seems to me this really is a very pressing question.

Miriam: You mean how gravity affects particles on that scale?

Vlatko Vedral: Quantum mechanics, that's right. How gravity and quantum mechanics coupled together. Can we explain gravity? Can we quantize it?

Miriam: Quantum mechanics describes light and matter, which exists as tiny discrete chunks. So quantizing gravity essentially means cutting up spacetime into similar minute bits and making them obey the loss of quantum mechanics.

But still though, I mean there's been a lot of debate about particle physics and these large, expensive experiments, not producing more particles, not finding evidence.

Vlatko Vedral: Yes.

Miriam: of supersymmetry.

Vlatko Vedral: Yes.

Miriam: And stuff like that. But there's also been these interesting hints that there might be a fifth force of nature. So I mean, should we be more excited about that? Why is the discussion sort of about how particle physics has failed because it might be on the verge of finding something really revolutionary?

Vlatko Vedral: You are right here. It's very difficult to make their judgement simply because these experiments are extremely complex. So even to come up with, um, next level of energy. So the whole idea, of course, is to probe smaller and smaller distances in shorter and shorter times. And because energy is inversely proportional to these things, this means that you require higher and higher. And of course that becomes extremely complicated already. These experiments that we have currently cost a huge amount of money, really, and it's not even clear whether we can scale them up to the next level, which is I think why people like me are looking for tabletop experiments that could tell us something. You know, maybe there are regimes that are simpler to access, but they could still tell us something.

But even having said this, I think, you know, if we can, I think it's worth pursuing high energy physics experiments. It is possible that they will tell us something new at new energies. And I think something of the kind that you are describing of another force that we have not been aware of would be a huge momentous discovery.

But you know, the decision whether we go in that direction is at least of all based on science, isn't it? Because it's really to do with us as a society, can we afford these things?

Miriam: And so if there were evidence of a fifth force of nature, would that say anything about quantum mechanics or general relativity or the various approaches to develop a theory of everything or a theory of quantum gravity? Would that give a hint about where we’re going?

Vlatko Vedral: Oh, absolutely. Uh, immediately. In fact, the first instinct would suggest that we should immediately think about this force in terms of the other forces as we understand them. So the first question there is, can we think about a mediator of this force, is there a kind of particle whose exchange leads quantum mechanically to this new force? So in other words, can we explain it in the same quantum mechanical way that we explain the electromagnetic interaction? That's always the case. Even the stronger, the weak forces are basically understood in exactly the same way as the electromagnetic force. If the answer is no, then this becomes very interesting actually, because it would be a different paradigm. That would, to me then, suggest that possibly we have to modify the way we understand quantum mechanics. But the first instance, I wouldn't go in the direction of modifying quantum mechanics. I would simply ask could this new fifth force also be quantized in the same way that the other forces are quantized?

Miriam: If a discovery of a new force of nature was announced, and this could be described by quantum mechanics, That would suggest that quantum mechanics is indeed fundamental and that any new forces or even gravity could potentially have quantum effects. But Chanda is still sceptical about the new experimental result.

Chanda Prescod-Weinstein: I need a 5 sigma result before I take anything seriously. It's funny because like I'm all for let's explore the thing until we are certain that we know it doesn't exist or until we discover it. And I'm fairly conservative when it comes to how much information I need before I agree that we have seen a thing that we have discovered a thing.So I'm all for tantalising hints. But as far as I'm concerned, those are just exciting possibilities until I see like a 5 sigma.

Miriam: So where are we at now? 3 sigma?

Chanda Prescod-Weinstein: One of those things is 3 sigma, and I think one of them might have even been like 2.5 sigma. Fine.

Miriam: Fine, these are hints and they have not been proven or anything like that. We don't know what these anomalies are. But if you had five sigma showing these results, what would that mean and what could it be?

Chanda Prescod-Weinstein: The question as to whether something would be interpreted as, say, a fifth force or another particle, I think it gets really interesting and just to pick maybe a simpler example, there are changes that we can make to our models of gravity to relativity that depending on how you write them down, they look like you've created a new particle like phenomenon. Or you can actually rewrite them to look like changes to the rules that govern how spacetime curves. And so I think that there would actually be like some interesting questions there about like what's the proper interpretation of these results. In that scenario, I think it would be a very exciting opportunity for theoretical physicists because like the best time for theoretical physicists is the time when we have no idea what's going on, when we have like a new result that's not consistent with our old results.

Miriam: Chanda says there may also be ways to experimentally rule out any such theories rather quickly. This would involve monitoring the life-cycle and evolution of stars.

Chanda Prescod-Weinstein: I will also just start by saying, this is not my area of expertise, but I will tell you that as an outsider, the first thing that comes to mind is actually that where I would have questions is about stellar astrophysics. And the reason that stellar astrophysics comes to mind is because stars are where everything happens kind of all at once. At the same time, you have really strong electromagnetic interactions, you have weak interactions, you have strong nuclear interactions, and gravity also plays a really big role, and you don't get what happens in a star without all four of those things working together simultaneously and in a way that we are relatively good at modelling. So we know about how many neutrinos should be produced in certain reactions, and we know that fusion is happening and that that fusion happens in a particular sequence. And this is actually something we understand so well. And so I actually think, you know, one of the challenges faced by any kind of new discovery at this scale is whether it messes up any of our stellar astrophysics so sufficiently that maybe there will be a conflict between this experimental discovery and what we know about how stellar astrophysics works.

Miriam: Ultimately, something needs to shift if we want a more fundamental understanding of nature, something which could explain everything we see around us, regardless of scale and including the particles in the standard model. But what exactly is a theory of everything?

Vlatko Vedral: So what we really think about theory of everything is unifying all the four fundamental forces, which is why frequently people talk about quantum gravity, because gravity is the only outstanding force that we are not able to unify with the other three. So what does that really mean?

It means writing down a quantity that goes under various different names in physics. It's a mathematical quantity called Lagrangian, or a Hamiltonian, or whatever you want to call it, but it's a quantity that would actually contain all of these forces in which you could simply use to calculate any experiment in principle, whatever experiment you want to perform, whatever forces this experiment may contain and depend on, this entity in this grant unified theory should be able to actually calculate ultimately. So that's kind of the holy grail of physics. It's of course a big question whether this is possible. So I think physicists are clearly aware that this may well be just an intuition and a dream, but it doesn't mean that nature works this way. You know, there is nothing out there that really necessitates this kind of description.

Miriam: You are listening to Great Mysteries of Physics from The Conversation. But the clash between quantum mechanics and general relativity isn't the only mystery of physics. Chanda works on dark matter, for example, which is an unknown substance which makes up most of the matter in the universe. Similarly, there is dark energy, an unknown force causing the universe to expand at an accelerated rate, which makes up most of the energy in the universe. So shouldn't a theory of everything explain these things too?

Chanda Prescod-Weinstein: I mean, is it a theory of everything if it's not about most things? So dark matter and dark energy are most of the matter energy content in the universe. So it's not really a theory of everything if it's not accounting for most of the matter energy content in the universe.

Miriam: But we, it goes back to what we were saying about is it just to theoretically bring together a quantum and general relativity that might not necessarily explain what those things are?

Chanda Prescod-Weinstein: This is why I'm glad we don't actually use theory of everything in our work, but I think if we were to go out and declare to the public that something was a theory of everything, that probably should do those things, that's one of the requirements if that's what we are going to be telling people, it is. Otherwise, I think you can call it like a fundamental theory of quantum gravity, and that doesn't necessarily have to explain dark matter. I might argue that I feel differently about the source of the cosmic acceleration, so it's commonly referred to as dark energy, and that actually can cause a lot of confusion because people might think that they're a very similar phenomena. They are similar phenomena socially in that they're both things that we don't understand what they are, and that's literally when the cosmic acceleration problem and the question of why spacetime is not only expanding, but the speed of that expansion is increasing with time. When that came along, people were like, well, let's just call this dark energy because we called the last thing we were confused about dark matter. So really the thing they have in common is our confusion, which is not necessarily a physical commonality except that they're both matter energy content that we are unsure about. The reason that I wonder about dark energy in a distinct way from dark matter with respect to a theory of quantum gravity, because I do think that the presence of cosmic acceleration is maybe a hint about the nature of quantum gravity, because one way to think about that problem is that the nature of the vacuum, as you conceive of it in general relativity and the nature of the vacuum as you conceive of it in quantum fuel theory, when you try and put those two notions of the vacuum together, they don't agree.

And that's really… there's a mismatch there. So then we go out and make measurements, and the measurement is giving us a value that's not predicted by quantum fuel theory, and it's not predicted by general relativity. You can plug that value into general relativity and just say it's something we measure, it's not something the theory tells us, a priori, but in my ideal theory of quantum gravity, that's something that gets told to us, a priori, that our theory of quantum gravity says, ah, well it should have this value and this is why it has the value that it does. In the case of dark energy and really the cosmological constant, which is this thing that you can add to Einstein's equation and say, this is causing the acceleration and it's a form of vacuum energy.

There are a couple of like theoretical quandaries that come up. So one is, why is it so, so small? Because it's almost zero. But it's just big enough to be observably impactful. So that particular problem is really annoying when you try and then calculate from quantum field theory, what should the value be and the quantum field theory answer is off by 120 orders of magnitude. And if you assume that supersymmetry is real, you can shave 60 orders of magnitude off, but then you're still 60 orders of magnitude away.

Miriam: Exactly. Yeah. So you're saying that, you know, we want a theory for everything, whatever quantum gravity theory to explain what values things like the cosmological constants should have and other fundamental constants that we have no idea why they have the values they have.

Chanda Prescod-Weinstein: Right. So what is the value of the vacuum? At the very least, quantum gravity should be able to answer what the energy level of empty space is!

Miriam: And it should match with our observations?

Chanda Prescod-Weinstein: And it should match with our observations. So from my point of view, the fact of cosmic acceleration and the observation of an apparent cosmological constant is actually our first data point about quantum gravity.

Miriam: Vlatko agrees that a theory of everything really should explain everything.

Vlatko Vedral: That's actually this big question. Whether these things require any new concepts. So if dark matter and energy are really of different kind, something that is not already part of our standard model, let's say, then I think the theory of everything must also explain that.

Miriam: Do you think that people sometimes forget about those when you talk about a theory of everything?

Vlatko Vedral: I think so, and I think we forget about them possibly consciously, because there is a much bigger uncertainty about these things than about other things that we discussed, like the high energy experiments, of course, laboratory based experiments, which are even better confirmed. It seems to me that the degree of uncertainty there is much smaller. Then when we talk about dark energy and matter. So I think until that's kind of understood better, and we have even more experimental evidence, it seems to me that most people would not consider that yet as part of this grand unified theory. But ultimately, of course, it must be explained. It will have to be.

Miriam: But perhaps it makes sense to start with a theory that unites gravity and quantum mechanics. And such proposals already exist. One is string theory, which suggests that the universe is ultimately made up of tiny vibrating strings and different vibrations can give rise to different familiar particles– including a hypothesised but as yet undiscovered -- particle called a graviton that is related to gravity. But string theory makes one vital assumption that instead of the universe having three spatial dimensions, so with depth and height, plus one for time, it has 10, 11, or even more. And these different dimensions are compacted so tightly together that we don't really notice them at all, they're hidden. And each compactification describes a different possible universe with its own physical laws.

Another approach is called loop quantum gravity. While strength theory incorporates gravity as well as quantum mechanics, it sort of just assumes that Einstein's spacetime exists in the background. Loop quantum gravity, however, puts spacetime at the centre and then tries to show how it can arise from quantum effects. Essentially, the theory is trying to divide up spacetime into tiny chunks and show that it does behave quantum mechanically.

Chanda Prescod-Weinstein: And one of the strengths that people will point to with string theory is that string theory built on quantum field theory, which is the framework that we use to explain the standard model. And so the standard model was built into it. So this is essentially a picture where in order to bring them together, you have to move into higher dimensions. I think that that's probably the most user-friendly way of talking about it, and I think it does have a genuine strength, which is that it brings the whole standard model with it, which loop quantum gravity doesn't do, not in the same way. So loop quantum gravity takes the perspective that the goal should be to maintain the lessons of general relativity while bringing it into conversation with the framework of quantum mechanics and so possibly thinking about spacetime being quantized at the smallest scales, that's the broad brushstrokes picture of how loop quantum gravity sees things.

Miriam: As Chanda started her career in loop quantum gravity, how does she feel about it now? Has she changed her mind about the approach or does she still think it's the best theory?

Chanda Prescod-Weinstein: Oh man. I'm probably gonna get in trouble, but the good news is that I don't work on quantum gravity anymore, so I am just speaking from the peanut gallery at this point. So like I did my PhD ostensibly on cosmology and loop quantum gravity and loop quantum gravity is one particular approach to quantum gravity, and I would say that one of the critiques that's been lobbed at loop quantum gravity is that it's insufficiently ambitious. Because what loop quantum gravity is trying to do is explain in a coherent mathematical picture the quantization of spacetime and really how you think of like a quantum general relativity. That might be one way of just saying a quantum general relativity. And I don't know, maybe this is an ambition and I'm being shortsighted here, but the way that it was framed to me as a student was the goal was not necessarily to explain neutrinos and neutrino masses, that you can think of the standard model as something that connects to that picture. But the standard model is not going to be explained by it. And this is really a perspective difference from, say, string theory, which Lee Smolin was one of my PhD advisors and I came of age right as he put out ‘The Trouble With Physics’, which a lot of people saw as kind of like anti string theory warfare.

So I'm very much shaped by that particular moment in science where people were talking a lot about loop quantum gravity versus string theory. I think as a student, I thought I was just evaluating the scientific picture, but I do think that there was a social evaluation there, and it's true that I got an opportunity in Loop quantum gravity and was welcomed in in a way that I wasn't in string theory. String theory is in some ways far more fantastical. It builds on the framework of quantum field theory, which is something that we know we've tested and works, but it also requires extra dimensions that we've never seen, right? And so I think that that's very easy to capture the public's attention with it because it has all of these really fantastical features and you have all of these folks who are really excited about that. And it depends on which theories. Some of them, I think there are 11 spacetime dimensions and some there are 26. Not my area of expertise, obviously, because I chose the other side. I guess to go back to your question, maybe agnostic is the word? I think my job as a scientist is to be creative and interested and also to be willing to be told no by the universe.

Miriam: Vlatko, who is a quantum physicist, is quick to point out that if loop quantum gravity turns out to be correct, it would suggest that quantum mechanics is more fundamental than general relativity.

Vlatko Vedral: So it's what people would call a canonical, just is another name for standard. It's a standard way of quantizing something. So what that means is you take certain elements of general relativity. So general relativity, for instance, would talk about volumes of space or it would talk about areas or distances or intervals of time. And then you would think what they would mean quantum mechanically, what does it mean to quantize a volume? What does it mean to have a classical volume but actually to behave like a quantum mechanical object? So I think loop quantum gravity is a standard way of imposing, if you like, quantum mechanics on general relativity.

So I think people in loop quantum gravity would certainly bet on the fact that quantum mechanics wins, if you see what I mean, over general relativity and general relativity will have to conform to quantum mechanics. And it seems to me that both string theory and loop quantum gravity, as well as more or less any, hat I called canonical, standard quantization approach, that all of them would agree that gravity is quantum at that level. So I don't think there would be a disagreement there. So what that means is that in order to really see how these theories differ, you would have to ramp up the gravitational strength.

And what that means is that it's very hard for us to test it because now you have to take a larger and larger object, which make means it gravitates more and more, and then be able to put it in a quantum superposition of being in two or more states at the same time. And this is exceedingly difficult actually.

Miriam: So testing a theory of everything won't be easy. But is it impossible?

Vlatko Vedral: I don't think it's impossible. We probably have to think harder about it because frequently, even with ordinary quantum mechanics, we are talking about effects that are tiny, right? Because we usually talk about this Planck's constant as being your quantum of action, if you like. And unless you are close to these regimes where Planck's constant matters if you like, it's gonna be very hard to see genuine quantum effects. But we know the quantum effects can be amplified to the macroscopic scales that, that they actually do matter at macroscopic level. You know, things like, for instance, superconductivity, it's a genuine quantum effect, it really is an effect that can be seen at objects that are visible. You know, these supercurrents that are generated in superconductors are actually macroscopic currents, and yet they exist in superposition of different classical states, if you like. So you know, I'm always optimistic that even when some theories claim that some of these effects are tiny, for instance, the scales at which space is discretized. People say, oh, these are tiny dimensions. This is something like 10 to the power of minus 35 metres, Planck’s distance. And some people say, oh, we are never gonna be able to do experiments to test these kind of distances. But what's not clear to me is whether these kind of effects could actually be amplified to lead to some things that are significant, even at our scales.

So it doesn't mean that we have to observe them directly. We could observe them indirectly through some manifestations providing that. Of course, we understand what these manifestations are. After all, think about cosmology. You know, cosmology suggests that all the objects in the universe we observe now, all the huge astronomical objects such as stars, clusters of stars, galaxies, clusters of galaxies, in fact, can be traced back to quantum fluctuations in the early universe. And so it's amazing you could actually argue that the whole classical structure of the present universe owes its existence to quantum fluctuations of geometry in the early state. It's a very speculative idea, but it's a possible idea. So that's why I'm somehow always optimistic that even if you have a theory where the effects seem very hard to reach, it's possible that actually they have consequences which are really macroscopic and could be used as witnesses of these effects.

Miriam: Vlatko has an idea for an experiment to test quantum gravity developed with Chiara Marletto, which you can hear about in episode four of the series. But he's also optimistic about experiments in space. In labs on the ground, physicists have already created exotic quantum states called Bose-Einstein condensates, for instance, and have also shown that it is possible to transmit or teleport information about a quantum state from one location to another. But could these be replicated in satellites?

Vlatko Vedral: People are thinking about, you know, creating Bose condensates in space, making quantum superpositions on satellites and so on. And this has many advantages in the sense that you could actually amplify certain gravitational effects, you could suppress other effects. And these satellite experiments would be different to earth-based experiments. You could actually test different components of gravity on these satellites than what we are able to test on our planet. So that's certainly already moving away a little bit from earth-based experiments. People are suggesting some very exciting variations there.

Miriam: Like what? Can you give an example?

Vlatko Vedral: There are these very cute nanosatellites. I mean, they are tiny in the sense that they have dimensions 10 centimetres by 10 centimetres by 10 centimetres. So they're really small as satellites go. But in fact, you could compress many of our earth-based quantum experiments into this kind of volume, and that's remarkable as well. The state of engineering is simply mind-blowing at present, that you could take a whole laboratory. That's huge you know, we are talking about large rooms basically, and you could compress all of that atom optics into this kind of nano satellite cube. And I think what would be interesting already to test is whether the same quantum principles are obeyed in these kind of experiments. Could you really make a superposition of different massive objects on a satellite as well? Could these objects interfere quantum mechanically? Could you get them entangled? Could you teleport on these satellites?

Miriam: But isn't it like they would be in sort of free fall, so microgravity?

Vlatko Vedral: Indeed.

Miriam: So wouldn't it be easier then to see those effects or?

Vlatko Vedral: Some of it, because I think if you're talking about the effects within the objects in these super positions, exactly, then that would be easier to see because they would effectively be in free fall as you say, you would eliminate all other gravitational fields, which is why some people are advocating that that's the way to go. But bear in mind that we've never done any quantum experiment there. So I think even confirming that some of these basic experiments work the way we think they ought to work is also an open question.

Miriam: What would that say about quantum mechanics? That it is more fundamental than gravity or?

Vlatko Vedral: I think it would be yet another confirmation of quantum effects at that level. Yes. To me, that would also signal that this works even in this different setting.

Miriam: Whether we will ever have experimental evidence for any approach to uniting quantum mechanics and general relativity is hard to say, but Chanda thinks we need to be patient.

Chanda Prescod-Weinstein: I think one challenge that we're facing right now is that for most of the last century, physicists and the general public have gotten a little bit spoiled. It was a time of extraordinary learning at a rapid pace about particle physics, so about the smallest fundamental constituents of matter. And as far as I know, there is no cosmic rule saying that physics has to be like that all the time. I, I think that we now have a social expectation that doesn't necessarily align with how the universe works. Like the universe is not designed to be understandable on the time scale of a human lifetime. There's no cosmic rule that says that dark matter, which is the problem that I work on, has to get resolved before I die. It could be like I die and like the next day is the day that like a detector goes off. Like that could be it, right?

Miriam: Or maybe it's like, ages away when there's like some sort of post-human AI species…

Chanda Prescod-Weinstein: Right? I mean, it kind of doesn't matter what I think, right? The universe is just gonna calculate regardless of what I think about how it should be calculating. And I've spent most of my career as a professor and as a postdoc working on a hypothetical dark matter candidate, the axion. The axion might be forever hypothetical. It may not in fact be the dark matter. I have to be ready for that. I can't be the kind of person who refuses to accept data because it doesn't line up with my worldview

Miriam: From a lack of new particles being discovered to fundamental clashes between different theories, you may wonder whether physics is ultimately broken. But as we've seen in this episode, there are lots of theoretical physicists working on various proposals for creating a theory of everything, from string theory to loop quantum gravity. Yes, each suffers from its own set of challenges, but perhaps the theorist will soon be guided by experiments. Perhaps they'll discover that quantum mechanics and general relativity aren't as incompatible as we previously thought, and perhaps they'll glean insights into which one is most fundamental.

But let's not forget that physicists are people too. As Vlatko pointed out, they may be drawn to certain theories because the maths is more closely aligned with their own thinking. And as Chanda pointed out, perhaps some bright young minds out there are put off from pursuing certain ideas because they don't feel they fit in in the community. A theory of everything sounds like something that transcends human experience, but proposals are being created within the messy realm of human beings, full of beliefs, hunches, experiences, and prejudices.

But despite that, humanity has got pretty far in understanding the cosmos. And that might be because we all have different perspectives and different ideas. We also have tremendous levels of curiosity and creativity, which when coupled with a rigorous scientific method, can achieve the seemingly impossible. So we thought we'd end the series with some different thoughts and perspectives on whether physics actually is broken from the brilliant minds who are tackling these mysteries every single day.

Natalia Ares: It's more like we are starting to uncover different parts of this story and just to make sense of the whole thing is very hard knowing just little bits, uh, here and there. But that's why we need more experiments to try and push these theories to the limit and try and see what comes next and which pieces are we missing.

Sean Carroll: Uh, the closest to a real problem that we're facing is that our theories are too good.So that makes life hard.

Chanda Prescod-Weinstein: I feel like we are using the best tools that we have available to us to answer really difficult and really interesting questions, and it would be so incredibly arrogant of us to think that we would answer those questions quickly.

Fred Adams: I think physics is always evolving. What happens is that certain areas of physics become more active and other areas of physics become more difficult to move forward in. So I think that there's always a changing of what's the next big thing.

Sabine Hossenfelder: It would be terrible if we ran out of mysteries. Um, what worries me more is that we don't seem to make any progress on solving those mysteries. So what you'd expect to happen is that we solve one mystery and then a new one pops up. But what's actually been going on, at least in the foundations of physics, is that we're still discussing the same questions that we have been discussing for a hundred years.

Paul Davies: Uh, most of the running so far has been in the very small and the very large particle physics and cosmology. But now increasingly physics is tackling the very complex. That's the third great frontier, and this is where physics and biology intersect. Um, and I think that there's still huge opportunity for physics to move into those fields and, uh, to maybe develop new laws and principles to describe them.

Katie Mack: I think that it's been extraordinarily successful. I mean, look at what we know. We have an extremely successful model of the entire history of the universe from the tiniest fraction of a second to now, we can observe the cosmic microwave background, the light from the Big Bang itself. We can observe the expansion of the universe. We can see galaxies that existed in the first couple of a hundred million years after the beginning of the cosmos. We have general relativity. We have quantum mechanics. We're creating quantum computing. I think that physics is going great.

Andrew Pontzen: I think it's a sign that there's a lot of exciting questions to be answered and you know, what would you rather have? Would you rather have a physics where everybody agrees on the correct direction of travel and we just, you know, tick things off and basically dot the I and cross the Ts? I mean, that sounds utterly boring to me, and I wouldn't be a physicist if that was the situation we're in. Physics is wide open and there's a lot of genuine disagreements about what we should be doing next, but for me, that's actually just part of the excitement on equations.

Chiara Marletto: Physics isn't broken, I think the more problems there are in it the better it is for physics because y'know we don't run out of jobs. I think it is very fruitful that there are problems that can be solved and even if we haven't been able to solve them so far it just means we haven't looked at it from the right angles.

Sara Walker: I don't think it's broken. I just think it's adolescent. I mean, it was only invented by our species about like 300 years ago. So I think that our theories of physics are very early and there's just a lot of work to be done. And you know, the most interesting places are the places where our theories are breaking because it's telling us that we're missing things about how reality works.

Vlatko Vedral: I feel very lucky to be alive at this point in time where I think we are about to see another revolution in physics. All my bets are that we are gonna sooner or later be forced to come up with a new theory, and I think it will supersede both quantum mechanics and general relativity. I think physics is the only way to understand the universe.

Miriam: That was Natalia Ares, Sean Carroll, Chanda Prescod-Weinstein, Fred Adams, Sabine Hossenfelder, Paul Davis, Katie Mack, Andrew Pontzen, Chiara Marletto, Sara Walker, and Vlatko Vedral. And thanks to all our contributors throughout the series.

Although everyone we've interviewed across this series has a different perspective, none of them believe that physics is broken. There was a time when we thought that there was nothing new to discover in physics, and just because that is no longer true doesn't necessarily mean we're on the wrong track. But it may mean that the next level of insight is so radically different mathematically and experimentally that it will take time to get there.

Ultimately, we need patience and long-term thinking, something humans aren't that great at, but it is becoming increasingly clear that it is a skill we must nurture.

This podcast was created and presented by me, Miriam Frankel and produced by Hannah Fisher. The executive producers are Jo Adetunji and Gemma Ware, and the advisory editor is Zeeya Merali. The sound design is by Eloise Stevens, and music is by Neeta Sarl. Great Mysteries of Physics is a podcast from The Conversation UK with funding from FQxI.

This was the sixth and final episode of Great Mysteries of Physics from The Conversation. I hope you've enjoyed it as much as we have. Thanks so much for listening.